

HIGH-Z QUASARS IN THE $R_H = ct$ UNIVERSE

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ABSTRACT

One cannot understand the early appearance of $10^9 M_\odot$ supermassive black holes without invoking anomalously high accretion rates or the creation of exotically massive seeds, neither of which is seen in the local Universe. Recent observations have compounded this problem by demonstrating that most, if not all, of the high- z quasars appear to be accreting at the Eddington limit. In the context of Λ CDM, the only viable alternative now appears to be the assemblage of supermassive black holes via mergers, as long as the seeds started forming at redshifts > 40 , but ceased being created by $z \sim 20 - 30$. In this paper, we show that, whereas the high- z quasars may be difficult to explain within the framework of the standard model, they can instead be interpreted much more sensibly in the context of the $R_h = ct$ Universe. In this cosmology, $5 - 20 M_\odot$ seeds produced *after* the onset of re-ionization (at $z \lesssim 15$) could have easily grown to $M \gtrsim 10^9 M_\odot$ by $z \gtrsim 6$, merely by accreting at the standard Eddington rate.

Keywords: cosmology: observations, theory; dark ages; reionization; early universe; quasars: general

1. INTRODUCTION

Quasars are the most powerful objects in the Universe. The efficient extraction of gravitational energy from matter falling onto their central supermassive black hole is sufficient to make them identifiable out to very large redshifts ($z \gtrsim 7$), where they can be studied to probe black-hole growth (e.g., Kauffmann & Haehnelt 2000; Wyithe & Loeb 2003; Hopkins et al. 2005; Croton et al. 2006) and the formation of large-scale structure in the early Universe (Fan 2006). For example, it is now believed that supermassive black holes played an active role in galaxy evolution, e.g., through their feedback on the interstellar medium, by heating and expelling gas that would otherwise have formed stars (see also Silk & Rees 1998; Di Matteo et al. 2005). However, the impact of studying high- z quasars is not limited to just these few examples; they can also provide crucial information on the re-ionization of the intergalactic medium (IGM) several hundred Myr after recombination.

One of the most useful observations of these sources has been the reverberation mapping of broad-lines, yielding the distance of the line-emitting gas from the central ionizing source. The measurement of the velocity of this plasma, e.g., via its Doppler-broadened line width, can therefore yield the gravitational mass of the central black hole to within a factor 3 or so (e.g., Wandel et al. 1999). This method has made it possible to determine black-hole masses for quasars beyond $z \sim 6$ (Willott et al. 2003; Jiang et al. 2007; Kurk et al. 2007; Kurk et al. 2009) and, combined with a measurement of the source spectrum, has helped us conclude that the most luminous high- z quasars contain black holes with mass $M \gtrsim 10^9 M_\odot$, accreting at close to the Eddington limit.

But the discovery of such massive objects so early in

the Universe's history (corresponding to an age of only ~ 800 Myr in the context of Λ CDM), and the apparent constancy of the observed quasar broad-line region properties with redshift (e.g., Pentericci et al. 2002), is quite surprising and difficult to understand in the context of the standard model. Indeed, the early appearance of supermassive black holes has developed into one of the most important unsolved mysteries in astronomy.

Their existence has resulted in diverse attempts to explain how such objects could have formed so quickly in the rapidly expanding early Universe. If one invokes standard Eddington-limited accretion, the e-folding time (i.e., the so-called Salpeter timescale) for black-hole growth is ~ 45 Myr, assuming an efficiency of 10%. Thus, reaching an observed mass of $10^9 M_\odot$ from a supernova-produced seed black hole of $5 M_\odot$ would have taken at least 860 Myr, longer than the short cosmic time available since the big bang.

Some workers have therefore suggested that super-Eddington accretion must have occurred at very high redshifts (e.g., Volonteri & Rees 2005). Others have proposed that rapidly spinning black holes accrete with higher efficiency (when the disk is spinning with a retrograde orbit), thereby lowering the Salpeter timescale (Shapiro 2005). It has also been demonstrated that Eddington-limited accretion can still account for these black holes, but only if the seeds were $\gg 5 M_\odot$. However, to produce high- z quasars in only ~ 400 Myr, the initial black hole masses would have had to have been greater than $\sim 10^{4-5} M_\odot$ (Yoo & Miralda-Escudé 2004).

All the proposals thus far appear to be contrived for one reason or another. Unless some exotic mechanism involving self-interacting dark matter was responsible, the resolution to this problem ultimately relies on an

enhanced accretion rate, or the creation of a seed mass much larger than we can currently explain. Observations of the local Universe indicate that seed black holes could have formed during supernova explosions following the Dark Ages (see § 2 below), but probably not with masses exceeding $\sim 5 - 20 M_\odot$. And now that we have detected over 50 high- z quasars, we also know that none of them appear to be accreting at greatly super-Eddington rates (see, e.g., figure 5 in Willott et al. 2010a).

In the context of the standard model, the only viable alternative now appears to be the role played by mergers in the early Universe, which may also be relevant—perhaps even essential—to creating the correlation between black-hole mass and host bulge mass observed nearby (see, e.g., Tanaka & Haiman 2009; Lippai et al. 2009; Hirschmann et al. 2010). However, in order to make this work, the black-hole seeds would have had to form well before the currently understood beginning of the period of reionization, and their creation would have had to cease by a redshift of $\sim 20-30$ in order to not over-produce the mass density in lower-mass (i.e., between a few $\times 10^5 M_\odot$ and a few $\times 10^7 M_\odot$) black holes. We will continue our discussion of this possibility in the Conclusions section.

In this paper, we advance an alternative viewpoint—that the difficulty faced by Λ CDM in accounting for the high- z quasars is actually more evidence against it being the correct cosmology. We show that the problems faced by Λ CDM disappear when we instead interpret the origin and evolution of the high- z quasars in the context of the $R_h = ct$ Universe. In particular, we will demonstrate that in this cosmology, high- z quasars appeared only after the beginning of the Epoch of Re-ionization (EoR), as one would expect if their $5 - 20 M_\odot$ seeds were created from the deaths of Pop II and III stars.

2. THE DARK AGES AND EPOCH OF RE-IONIZATION

The explanation for how and when the high- z quasars came into existence is necessarily woven into the history of the Dark Ages and the EoR that followed. In the context of Λ CDM, the Universe became transparent roughly 0.4 Myr after the big bang, ushering in a period of darkness that ended several hundred Myr later, when the first stars and galaxies started forming and emitting ionizing radiation. The current constraints delimit the EoR to the redshift range $z \sim 6 - 15$ (Zaroubi 2012), which (again in the context of Λ CDM) corresponds to a cosmic time $t \sim 400 - 900$ Myr.

The IGM was neutral at the beginning of the EoR, but an evolving patchwork of neutral (HI) and ionized hydrogen (HII) unfolded as the re-ionization progressed. The temperature and ionized fraction of the gas increased rapidly as the number of ultraviolet sources formed, until the ionized regions eventually permeated the whole Universe (Barkana & Loeb 2001; Bromm & Larson 2004). Some of the best probes of this re-ionization process are actually the high- z quasars themselves. High-resolution spectra of SDSS high- z quasars show a complete absence of structure bluewards of the quasar Lyman- α restframe emission, especially those with redshift $z \gtrsim 6$ (Fan et al. 2006). This is interpreted as due to an increase in the Lyman- α optical depth resulting from the decrease in the ionized fraction along the line-of-sight. The fact that

the trend is not monotonic with redshift, may also be an indication that we are witnessing the aforementioned patchwork of ionization at these redshifts. The main conclusion from the Lyman- α optical depth measurements is that the Universe was highly ionized at $z \lesssim 6$, but its neutral fraction increased with increasing redshift, presumably reaching a value ~ 1 by $z \sim 15$. Support for these results is also provided by the Wilkinson Microwave Anisotropy Probe (WMAP, Bennett et al. 2003) mission, whose measurements suggest that the Universe may have been $\sim 50\%$ neutral at $z \gtrsim 10$, and that re-ionization did not start before $z \sim 14$ (Page et al. 2007).

Hydrogen is ionized by photons with energy $\gtrsim 13.6$ eV. Obvious candidate sources are Pop II and III stars. The constraints on decaying or self-annihilating dark matter particles, or decaying cosmic strings, make it unlikely that these could re-ionize the Universe on their own (see, e.g., Ripamonti et al. 2007). Accreting supermassive black holes also produce large quantities of UV and X-radiation, but their mass distribution in the early Universe is not fully known, rendering the role played by quasars during re-ionization somewhat uncertain (see, e.g., Meiksin 2005). We can therefore reasonably conclude that the EoR was brought about by a combination of Pop II and III stars in star-forming galaxies and the ionizing radiation produced by the high- z quasars that formed during this period. The latter may have become more important towards the end of the EoR, though it is not clear if they, by themselves, could have caused the Universe to become fully ionized by redshift $z \lesssim 6$ (Jiang et al. 2006).

Let us now examine how the high- z quasars observed thus far impact this basic picture when viewed from the perspective of Λ CDM. In Table 1, we list many of the objects for which a reliable determination of mass has been made. This is not a complete sample, but is probably quite representative of the overall distribution. The columns in this table are as follows: (2) the quasar’s measured redshift, (3) its inferred mass, quoted as a range when the uncertainty is well defined, (4) the quasar’s age, calculated from its redshift, using the Universe’s expansion history according to Λ CDM, (5) the quasar’s age (for the same redshift) calculated using $R_h = ct$, (6) the cosmic time at which a $5 M_\odot$ seed must have formed in order to grow into the observed quasar, assuming Eddington-limited accretion in the context of $R_h = ct$, and (7) the same as column (6), except for a seed mass of $20 M_\odot$.

Our analysis in this paper is based strictly on the premise that black-hole seeds are produced in supernova events, which observations in the local Universe indicate result in $\sim 5 - 20 M_\odot$ remnant cores. We further avoid any possible exotic mechanism that might have enhanced their accretion rate above the Eddington limit, defined from the maximum luminosity attainable due to outward radiation pressure acting on highly ionized infalling material (see, e.g., Melia 2009). This power depends somewhat on the gas composition, but for hydrogen plasma is given as $L_{\text{Edd}} \approx 1.3 \times 10^{38} (M/M_\odot)$ ergs s^{-1} , in terms of the accretor’s mass, M . The accretion rate \dot{M} is inferred from L_{Edd} , once the fractional efficiency η of converting rest mass energy into radiation is identified. Matter spiraling inwards towards the event horizon releases a minimum of $\sim 6\%$ of its rest energy for a Schwarzschild

Table 1
High- z Quasars

Name	z	$M/10^8 M_\odot$	Age/Myr (Λ CDM)	Age/Myr ($R_h = ct$)	Seed/Myr ($5 M_\odot$)	Seed/Myr ($20 M_\odot$)	Ref.
ULAS J1120+0641	7.085	~ 20	737	1,634	743	805	Mortlock et al. (2011)
CFHQS J0210-0456	6.440	0.4–1.4	834	1,776	1,004	1,123	Willott et al. (2010a)
CFHQS J2329-0301	6.430	~ 2	836	1,778	990	1,052	Willott et al. (2007)
SDSS J1148+5251	6.419	20–123	838	1,781	808	952	Fan et al. (2002)
							De Rosa et al. (2011)
CFHQS J2329-0301	6.417	2.1–2.9	838	1,781	977	1,053	Willott et al. (2010a)
SDSS J1030+0524	6.280	8–12	862	1,815	947	1,027	Pentericci et al. (2002)
CFHQS J0050+3445	6.253	22–31	867	1,822	911	989	Willott et al. (2010b)
QSO J1623+3112	6.220	12–18	874	1,830	943	1,024	Wang et al. (2007)
SDSS J1048 + 4637	6.198	16–98	877	1,835	872	1,016	De Rosa et al. (2011)
CFHQS J0221-0802	6.161	2.3–14.5	885	1,845	968	1,113	Willott et al. (2010b)
CFHQS J2229+1457	6.152	0.7–1.9	886	1,848	1,063	1,170	Willott et al. (2010b)
CFHQS J1509-1749	6.121	27–33	892	1,855	941	1,013	Willott et al. (2007)
CFHQS J2100-1715	6.087	9.2–12.3	897	1,863	995	1,069	Willott et al. (2010b)
SDSS J0303-0019	6.080	1.5–3.8	899	1,866	1,049	1,154	Kurk et al. (2009)
SDSS J0353 + 0104	6.072	6–35	900	1,868	952	1,093	De Rosa et al. (2011)
SDSS J0842 + 1218	6.069	7–43	901	1,869	943	1,025	De Rosa et al. (2011)
SDSS J1630 + 4012	6.058	3.6–22.5	903	1,872	975	1,120	De Rosa et al. (2011)
CFHQS J1641+3755	6.047	1.6–3.4	906	1,876	1,064	1,161	Willott et al. (2007)
SDSS J1306 + 0356	6.018	7–43	911	1,882	956	1,100	De Rosa et al. (2011)
SDSS J1308+0356	6.016	10–12	911	1,883	1,015	1,085	Jiang et al. (2007)
SDSS J1306+0356	5.990	2.0–2.8	916	1,890	1,087	1,165	Jiang et al. (2007)
CFHQS J0055+0146	5.983	1.7–3.3	917	1,892	1,082	1,174	Willott et al. (2010a)

black hole, but η may be as high as 0.3 (or more) when the black hole is spinning (and the disk is on a prograde orbit), permitting frictional dissipation to continue down to radii smaller than ~ 3 Schwarzschild radii (e.g., Melia 2009). Most workers adopt the “fiducial” value $\eta = 0.1$, reasonably close to the Schwarzschild limit, but also allowing for some influence from a possible black-hole spin. This is the value we will assume here.

For simplicity, we will also ignore the contribution to black-hole growth from mergers, which almost certainly must have occurred at some level and, as we have already indicated in the introduction, may have been necessary in order to produce their final distribution and intrinsic scatter in black-hole versus galaxy mass relations (Hirschmann et al. 2010). The constraints we will derive below should therefore be viewed with this caveat in mind.

Under these conditions, the maximum accretion rate experienced by quasars at high redshift was then $\dot{M} = L_{\text{Edd}}/\eta c^2$, which grew their mass at a rate $\dot{M} \approx 0.022 (M/M_\odot) M_\odot/\text{Myr}$. Solving for the mass as a function of cosmic time then produces the Salpeter relation,

$$M(t) = M_0 \exp \left(\frac{t - t_{\text{seed}}}{45 \text{ Myr}} \right), \quad (1)$$

where M_0 is the seed mass produced at time t_{seed} . We have calculated the time t_{seed} for each of the quasars in Table 1, using the Universe’s expansion history in Λ CDM, for two values of the seed mass, $M_0 = 5 M_\odot$ and $20 M_\odot$. In each case, the possible range of “birth” times (between these two limits) is shown against the redshift of the observed quasar in figure 1, for the assumed cosmological parameters $H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.28$, and a dark-energy equation of state $p = -\rho$.

In this figure, we also show the period of Dark Ages and the EoR, the latter identified from its measured redshift range ($z \sim 6 - 15$). The evident problems with this

diagram are well known by now and we do not need to dwell on them. We simply point out the rather obvious flaws with this model, in which all of the quasars in this sample had to begin their evolution from seeds formed around the time of the big bang, well before the EoR even started. Worse, as quasars continue to be discovered at greater and greater redshifts, the model becomes completely untenable. Already, ULAS J1120+0641 (discovered at redshift 7.085; Mortlock et al. 2011), and SDSS J1148+5251 (discovered at redshift 6.419; Fan et al. 2002), must both have started their growth phase well before the big bang, which makes no physical sense.

These are the reasons, of course, why investigators have been motivated to propose exotic methods of greatly enhancing the accretion rate and/or starting from much bigger seed masses. But as we have already suggested in the introduction, our proposal in this paper is that the black-hole birth and evolution were in fact quite standard (as we understand these from observations in the local Universe), and that the answer lies instead with the assumed cosmology. Next, we will move to a consideration of how the observations are interpreted in the context of the $R_h = ct$ Universe.

3. THE $R_h = CT$ UNIVERSE

Whereas Λ CDM is an empirical cosmology, deriving many of its traits from observations, the $R_h = ct$ Universe is an FRW cosmology whose basic principles follow directly from a strict adherence to the Cosmological Principle and Weyl’s postulate (Melia 2007; Melia & Shevchuk 2012; see also Melia 2012a for a more pedagogical treatment). By now, these two expansion scenarios have been compared with each other, and with the various cosmological measurements, both at low and high redshifts. The evidence suggests that $R_h = ct$ is a better match to the data, particularly the CMB, whose fluctuations are so different from the predictions of Λ CDM that its probability of being the correct description of

nature has been assessed at $< 0.03\%$ (Copi et al. 2009). On the other hand, the $R_h = ct$ Universe explains the CMB angular correlation function very well, particularly the observed absence of any correlation at angles greater than $\sim 60^\circ$ (Melia 2012b). A short summary of the current status of this cosmology appears in Melia (2012c).

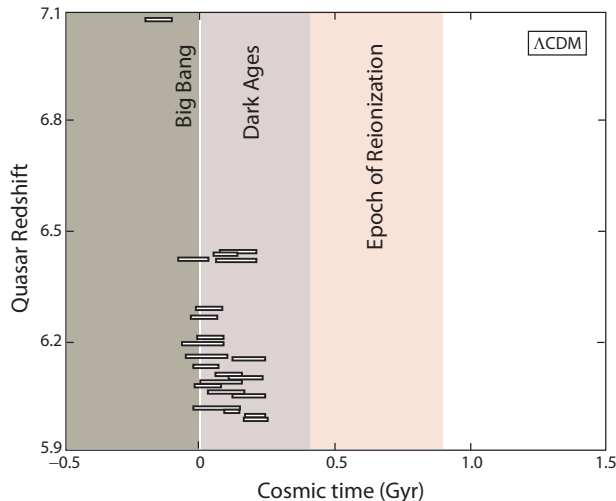


Figure 1. Cosmic time t (horizontal axis) at which the seed black hole, with a mass in the range $5 - 20 M_\odot$, would have had to appear in order to produce the corresponding quasar (from Table 1), observed at the redshift indicated on the vertical axis, via Eddington-limited accretion. The Epoch of Re-ionization (EoR) is limited roughly to the redshift range $\sim 6 - 15$, which in Λ CDM corresponds to $t \sim 400 - 900$ Myr. The Dark Ages ($t \sim 0.4 - 400$ Myr in Λ CDM) is the period between recombination (at ~ 0.4 Myr in Λ CDM) and the onset of re-ionization.

Insofar as accounting for the high- z quasars is concerned, the essential feature of the $R_h = ct$ Universe that distinguishes it from Λ CDM is its expansion factor, $a(t) \propto t$. Therefore, the cosmological redshift is given as

$$1 + z = \frac{t_0}{t_e}, \quad (2)$$

where t_0 is the current age of the Universe and t_e is the cosmic time at which the light with redshift z was emitted. In addition, the gravitational horizon R_h is equivalent to the Hubble radius $c/H(t)$, and therefore one has $t_0 = 1/H_0$. These equations are sufficient for us to produce a diagram like that shown in figure 1, except this time for the $R_h = ct$ Universe, and this is illustrated in figure 2. Note that the EoR redshift range $z \sim 6 - 15$ here corresponds to the cosmic time $t \sim 830 - 1,890$ Myr, and so the Dark Ages did not end until ~ 830 Myr after the big bang.

The most striking feature of this diagram, however, is that not only did all the high- z quasars have time to grow after the big bang, but that all of the $5 - 20 M_\odot$ seeds that grew into these sources formed *after* the EoR had started. This is exactly what one would have expected if these seeds were produced from Pop II and III supernovae, which presumably occurred after these stars had time to evolve and begin re-ionizing the Universe. To be clear, what these results are telling us is that in the $R_h = ct$ Universe, all of the high- z quasars listed in Table 1 started their growth at redshift $z \lesssim 15$, and developed into $M \sim 10^9 M_\odot$ supermassive black holes by

redshift $z \gtrsim 6$. And all of this happened with standard astrophysical principles, as we know them. There was no need for anomalously high accretion rates, nor the exotic creation of very large seed black holes.

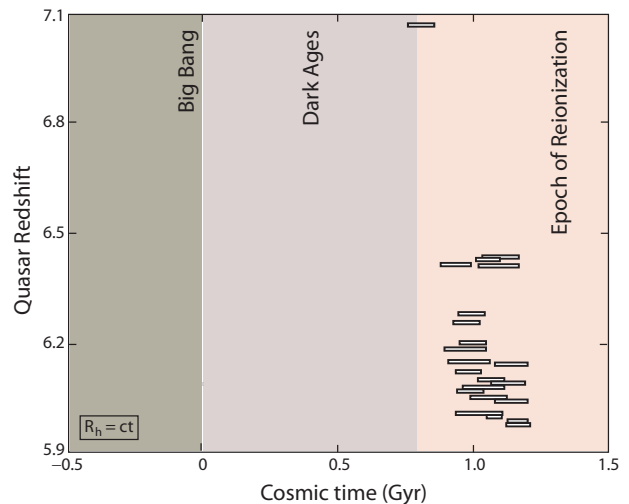


Figure 2. Same as figure 1, except here for the $R_h = ct$ Universe. In this case, the EoR corresponds to $t \sim 800 - 1,900$ Myr, and the Dark Ages extend up to ~ 800 Myr. Notice the close correspondence between the EoR and the appearance of the $5 - 20 M_\odot$ seed black holes that formed the quasars we see at $z \gtrsim 6$.

4. CONCLUSIONS

It is difficult to understand how $\sim 10^9 M_\odot$ black holes appeared so quickly after the big bang without invoking non-standard accretion physics and the formation of massive seeds, both of which are not seen in the local Universe. The more recent data have compounded the problem by demonstrating that most (if not all) of the high- z quasars appear to be accreting at the Eddington limit.

Within the framework of the standard model, it therefore appears that mergers must have played a key role, not only in producing the observed correlations between black-hole mass and host bulge mass in the local Universe (Hirschmann et al. 2010), but perhaps also in assembling the $10^9 M_\odot$ black holes seen at $z \sim 6 - 7$. However, the former outcome does not necessarily guarantee the latter. An important finding of detailed merger simulations is that, irrespective of the initial seed profile, the black-hole population always converges towards a Gaussian distribution. Observations of supermassive black holes locally therefore allow for quite some flexibility in the initial conditions.

Of course, this is quite useful for Λ CDM because the merger hypothesis offers a viable mechanism by which the high- z quasars could have formed by $z \sim 6$. However, in order to comply with all of the available data, certain conditions must have prevailed at $z \gg 6$. The simulations (see, e.g., Tanaka & Haiman 2009) show that $\sim 100 M_\odot$ seeds must have started forming by $z \sim 40$, well before the EoR, and must have stopped being created, or accreted at severely diminished rates, by $z \sim 20 - 30$, in order to not overproduce the mass density observed in lower-mass (a few $\times 10^5 M_\odot$ to a few $\times 10^7 M_\odot$) black holes. Without this cutoff, these lower

mass black holes would have been overproduced by a factor of $\sim 10^2 - 10^3$.

These are all interesting possibilities and are permitted by the lack of any direct observational constraints on black-hole mergers. In principle, the *Laser Interferometer Space Antenna* (LISA) might have been able to detect such mergers, or place limits on them, in the mass range $\sim (10^4 - 10^7) M_\odot / (1 + z)$ out to $z \sim 30$ (Tanaka & Haiman 2009). But LISA may not become reality unless a reprogrammed mission can eventually be approved by ESA. Unfortunately, the question of whether mergers could have assembled the high- z quasars in under 800 Myr since the big bang may therefore not be resolved any time soon.

There is also the question of whether the formation of black-hole seeds in Λ CDM would be consistent with our improved understanding of the EoR. It appears that seeds would have formed quite early in the Universe's history, well before re-ionization started at $z \sim 15$. Additional work would have to be carried out to demonstrate that a sufficient number of seeds could have been produced by Population III stars shortly after the big bang, without any evidence of re-ionization appearing until much later, past the point where the creation of seeds stopped (at $z \sim 20 - 30$). It may not be possible to completely reconcile these opposing trends.

In this paper, we have suggested that the disparity between the predictions of Λ CDM and the observations is further evidence against this being the correct cosmology. We have shown that the high- z quasar data may instead be interpreted much more sensibly in the context of the $R_h = ct$ Universe, for which standard $5 - 20 M_\odot$ seeds forming after re-ionization had begun (at $z \lesssim 15$) could have grown to $\gtrsim 10^9 M_\odot$ supermassive black holes by redshift $z \gtrsim 6$, merely by accreting at the observed Eddington rate. Together with similarly compelling evidence from the CMB and the large-scale matter distribution, this comparison suggests that $R_h = ct$ is the correct cosmology and that Λ CDM is, at best, simply an empirically derived approximation to it, that nonetheless fails at high redshifts.

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